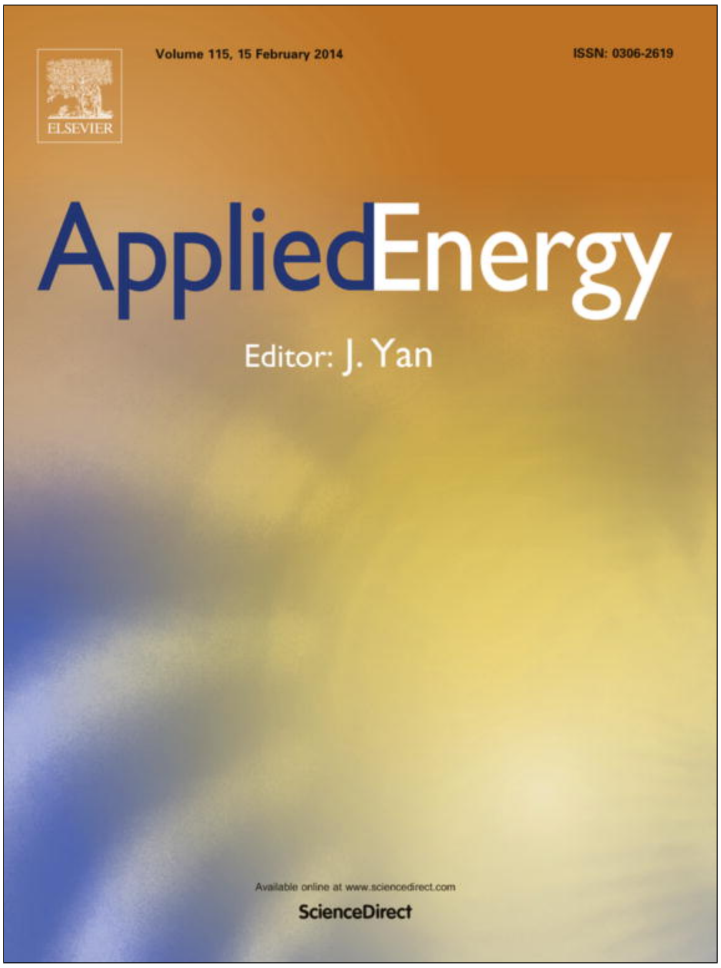
State-of-the-art analysis of the environmental benefits of green roofs

ARTICLE *in* APPLIED ENERGY · MARCH 2014

Impact Factor: 5.61 · DOI: 10.1016/j.apenergy.2013.10.047

1 AUTHOR:

Umberto Berardi
Ryerson University


Volume 115, 15 February 2014
ISSN: 0306-2619
ELSEVIER
AppliedEnergy
Editor: J. Yan
Available online at www.sciencedirect.com
ScienceDirect

Applied Energy 115 (2014) 411–428

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

State-of-the-art analysis of the environmental benefits of green roofs

Umberto Berardi [a,*], AmirHosein GhaffarianHoseini [b], Ali GhaffarianHoseini [c]

[a] Civil and Environmental Engineering Department, Worcester Polytechnic Institute, MA, USA
[b] Department of Civil and Architectural Engineering, College of Science and Engineering, City University of Hong Kong, Hong Kong
[c] Department of Architecture, Faculty of Design and Architecture, Universiti Putra Malaysia (UPM), Malaysia

HIGHLIGHTS

- Cross-disciplinary review is performed for showing benefits of green roofs.
- Green roofs have several benefits for energy, water and pollution management.
- Experiments show that green roofs must consider specific climatic conditions.
- Lifecycle analysis ensures the economic feasibility of green roofs.
- Quantification of the green roof performances needs to consider technical design.

ARTICLE INFO

Article history:
Received 13 August 2013
Received in revised form 23 October 2013
Accepted 28 October 2013
Available online 7 December 2013

Keywords:
Green roofs
Sustainable design
Low-energy buildings
Environmental benefits

ABSTRACT

Green roofs have been proposed for sustainable buildings in many countries with different climatic conditions. A state-of-the-art review of green roofs emphasizing current implementations, technologies, and benefits is presented in this paper. Technical and construction aspects of green roofs are used to classify different systems. Environmental benefits are then discussed mainly by examining measured performances. By reviewing the benefits related to the reduction of building energy consumption, mitigation of urban heat island effect, improvement of air pollution, water management, increase of sound insulation, and ecological preservation, this paper shows how green roofs may contribute to more sustainable buildings and cities. However, an efficient integration of green roofs needs to take into account both the specific climatic conditions and the characteristics of the buildings. Economic considerations related to the life-cycle cost of green roofs are presented together with policies promoting green roofs worldwide. Findings indicate the undeniable environmental benefits of green roofs and their economic feasibility. Likewise, new policies for promoting green roofs show the necessity for incentivizing programs. Future research lines are recommended and the necessity of cross-disciplinary studies is stressed.

Contents

* Corresponding author. Tel.: +1 508 831 6545.
E-mail addresses: uberardi@wpi.edu (U. Berardi), amirhosein_ghaffarian_hoseini@yahoo.com (A. GhaffarianHoseini), ali_ghaffarian_hoseini@yahoo.com (A. GhaffarianHoseini).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.10.047

Nomenclature

$C_{e,g}$ latent heat flux bulk transfer coefficient at ground layer
C_f bulk heat transfer coefficient
C_{hg} sensible heat flux bulk transfer coefficient at ground layer
$C_{p,a}$ specific heat of air at constant pressure
F_f net heat flux to foliage layer (W/m^2)
F_g net heat flux to ground surface (W/m^2)
h effective heat transfer coefficient with convection + radiation
h_{fg} latent heat of evaporation
H_f foliage sensible heat flux (W/m^2)
H_g ground sensible heat flux (W/m^2)
$I_s^{\downarrow}$ total incoming short-wave radiation (W/m^2)
$I_{ir}^{\downarrow}$ total incoming long-wave radiation (W/m^2)
l_f latent heat of vaporization at foliage temperature (J/kg)
l_g latent heat of vaporization at ground temperature (J/kg)
K total thermal conductivity
L characteristic depth of green roof
L_f foliage latent heat flux (W/m^2)
L_g ground latent heat flux (W/m^2)
LAI leaf area index (m^2/m^2)
m evaporation flow rate
q_{af} mixing ratio for air within foliage canopy
$q_{f,sat}$ saturation mixing ratio at foliage temperature
$q_{g,sat}$ saturation mixing ratio at ground temperature
Q_{cond} conduction heat
Q_{irr} radiation heat
Q_{conv} convection heat
Q_{evap} evapotranspiration heat
r'' surface wetness factor
T_{af} air temperature with in the canopy
T_f foliage temperature
T_g ground surface temperature
T_C temperature of cold space
T_S temperature of green roof surface
T_∞ ambient temperature
V_∞ air velocity
W_{af} wind speed within the canopy
α_f albedo (short-wave reflectivity) of the canopy
α_g albedo (short-wave reflectivity) of ground surface
ε_f emissivity of canopy
ε_g emissivity of the ground surface
ε_1 $\varepsilon_g + \varepsilon_f - \varepsilon_g \cdot \varepsilon_f$
φ_∞ relative air humidity
ρ_{af} density of air at foliage temperature
ρ_{ag} density of air at ground surface temperature
θ moisture content
σ Stefan–Boltzmann constant
σ_f fractional vegetation coverage

1. Introduction

It is repeatedly documented that approximately 40% of worldwide energy use is associated with the construction and maintenance of buildings [1–3]. Buildings are also responsible of the 33% of greenhouse gas emission globally. Due to the high rate of energy and resource consumption of buildings, various sustainable approaches and environmentally responsive energy efficient technologies have been proposed and implemented to realize low-energy buildings [2,3]. These include advanced eco-technologies, energy efficient systems and renewable energy sources. In this context, green roofs are often identified as a valuable strategy for making buildings more sustainable [3–5].

Green roofs are also named "eco-roofs", "living roofs" or "roof gardens", and are basically roofs with plants in their final layer [5,6]. Green roofs are generally built to enhance the energy efficiency of their buildings, but many other benefits exist. In fact, their vegetation layer realizes photosynthesis processes whereas their soil layer allows absorption of rainfall, often resulting in an improvement in water runoff quality [7].

This paper targets to develop a state-of-the-art analysis of environmental benefits of green roofs to help understanding their status, new trends, and potentials. Furthermore, it aims to identify multi-disciplinary insights for environmental benefits of green roofs. These have often been indicated as complex systems, which require collaborative efforts by architects, engineers, horticulturists, contractors, and urban planners [5,6]. The advantages of green roofs have determined the attention of different disciplines, with the result that research related to them is dispersed among many different journals in different fields [8]. By using a multi-disciplinary approach, this paper claims that the benefits and impacts of green roofs are highly interrelated with the goals of sustainable buildings [9]. Only papers published in the last ten years will be considered, with a higher attention to papers appeared after 2008.

The following section presents an overview of current interpretations and classifications of green roofs. Section three focuses on technical aspects and structure of green roofs. In section four, environmental benefits of green roofs, including energy reduction for cooling/heating purposes, urban heat island mitigation, air pollution reduction, rainwater management, noise reduction, and ecological preservation are discussed. Section five focuses on the economic feasibility of green roofs and on policies incentivizing their implementation. The study concludes by showing future directions of research, stressing the identified critical points and the respective solutions, and the ultimate potential of green roofs for promoting sustainability.

2. An overview of literature on green roofs

2.1. Background

Existing literature shows that several types of green roofs have been used in different countries for centuries with confirmed

benefits in different climatic conditions and building characteristics [10,11]. The early history of green roofs dates back to the fifth century when Babylon's hanging gardens were implemented [10]. Green roofs were also utilized in the ziggurats of ancient Mesopotamia [12]. Roman architecture also embraced roof gardens; for example, the Mysteries Villa represents such integration and offers an example of space that enhances human activities while improving aesthetic value and roof life [13]. Green roofs have also been presented in vernacular architecture in different countries; for example, Northern European countries (in particular Norway) used green roofs to increase the thermal insulation [4]. After many centuries of rare utilization during the modern age, green roofs have been rediscovered in the twentieth century by the Swiss architect Le Corbusier who included them in the five points of modern architecture [14]. Around the same time, American organic architects proposed green roofs as a method to integrate buildings and nature.

A more intensive implementation of green roofs started in German-speaking countries in the 1970s [15]. Green roofs gained popularity also in France and Switzerland in the same years [15,16]. Several applications of green roofs in North America have then emerged, especially in the area of Portland. It is of the last years that Japan has indicated green roofs as a prime technology to decrease the urban heat island and promote sustainable buildings [12]. The recent attention towards green roofs is demonstrated by dedicated conferences, associations, and competitions worldwide. Fig. 1 shows some of the 2012 Green Roofs for Excellence awards.

Green roofs are often indicated as a valuable solution for resolving the issue of the lack of green space in urbanized areas [18]. In fact, efficiently designed and integrated green roofs are valid alternatives to replace the lost green spaces and habitats in modern cities, and support life behaviors within nature [7]. However, based on current literature the energy-related performance of green roofs is still the most common benefit for which they are promoted and adopted [19–22]. Green roofs essentially prevent the penetration of solar heat to the covered building components [23–26]. Liu et al. denoted that *"they improve the thermal performance of a building through shading, insulation, and thermal mass"* [16]. Similarly, Saiz et al. affirmed *"the key property of a green roof is its low solar absorptance"* [27]. Previous energy-related interpretations of green roofs coexist with their significance as a space for the development of ecological biodiversity, with improved landscapes and enhanced air quality [27,28]. Several studies stressed the advantages for urban hydrology, storm water quality, and ecological habitats for wildlife [26]. In particular, several studies have focused on the ability of green roofs to mitigate water runoff quantity while improving its quality [29,30]. All these advantages will be reviewed in Section 3.

2.2. Possible classification of green roofs

Green roofs are generally classified as *extensive* or *intensive*, though some authors include a *semi-intensive* classification [31–34]. An intensive green roof is generally a roof garden with

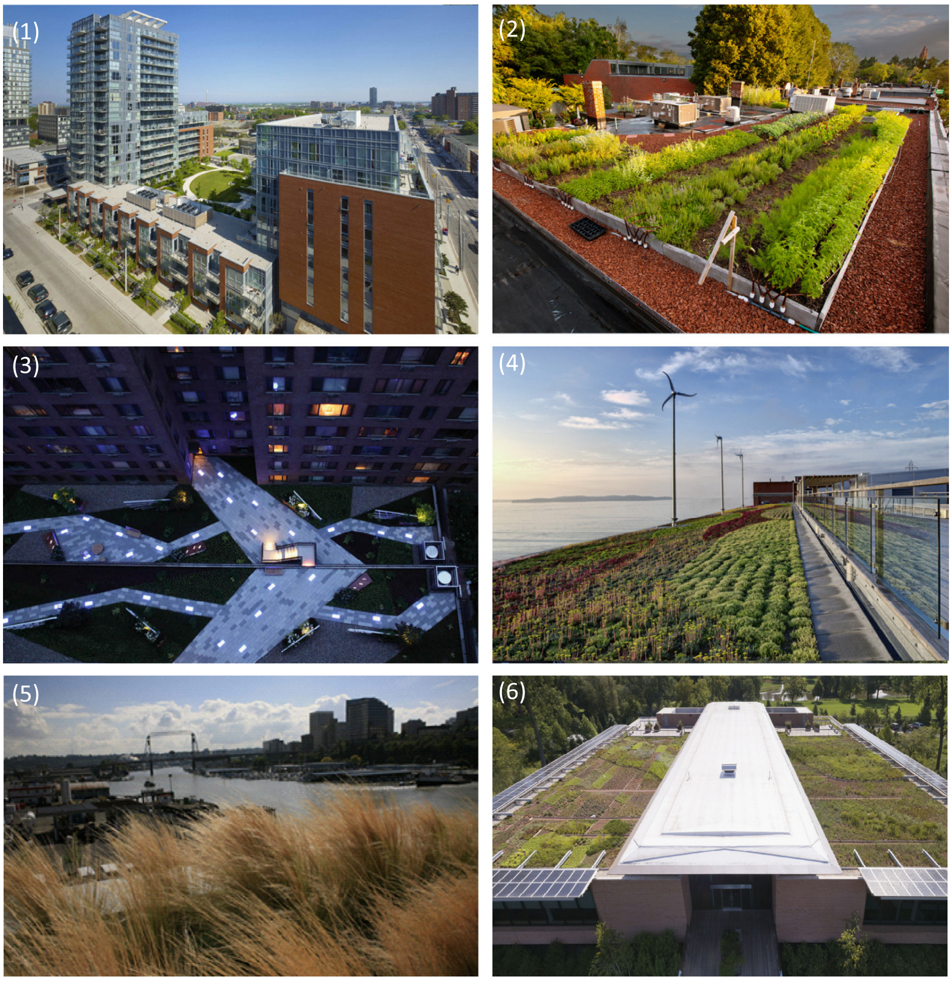


Fig. 1. Selected green roofs based on the 2012 Green Roof for Excellence Awards in buildings of different type: residential (1,2); commercial (3,4); institutional (5,6), pictures taken from [17].

Table 1
Classification of green roofs and their main attributes with supporting literature.

Main attributes	Extensive	Intensive	Source
Thickness of growing media	Below 200 mm	Above 200 mm	[18,34]
Accessibility	Inaccessible (fragile roots)	Accessible (usable for recreation purpose)	[18,34,38,39]
Weight	60–150 kg/m^2	Above 300 kg/m^2 (may require a reinforced structure)	[18,34,38,39]
Diversity of plants	Low (moss, herb and grass)	High (lawn or perennials, shrub and tree)	[7,18,34,38,41]
Construction	Moderately easy	Technically complex	[39,41]
Irrigation	Often not necessary	Necessity of drainage and irrigation systems	[7,38,39,41,43–45]
Maintenance	Simple	Complicated	[5,28,53]
Cost	Low	High	[11,23,39,49]

considerable depth of the soil layer, whereas an extensive green roof requires less depth of soil and assumes self-maintenance of the roof, and less water needs. Classifications into extensive and intensive roofs are also based on vegetation type, construction material, management and allocated usage [35–37]. Table 1 reports the main criteria of comparison between intensive and extensive green roofs.

Extensive green roofs weigh less and are appropriate for large sized rooftops while their construction process is technically simple and allows for implementation on sloped roofs. The types of plants that can be utilized for extensive green roofs are limited, and both the energy performance and storm water management potentials are relatively low [15,38].

On the other hand, in intensive green roofs, various types of plants can be implemented to create an appealing natural environment with improved biodiversity while also providing recreation space. Intensive roofs encompass comparatively better potential for improved insulation, enhanced storm water management and energy performances. However, their heavy weight may require a reinforced structure, and drainage and irrigation must generally be utilized increasing the technical complexity and associated costs [15,39].

Deeper green roofs produce lower heat gain and loss, and they often have a better thermal performance. A 10 cm increase in soil thickness increases the thermal resistance of dry clay soil by 0.4 m^2 K/W [40]. However, the presence and quantity of the water largely influence the thermal properties of the green roof. In fact, a wet roof provides additional evapotranspiration, which prevents the heat flux into the building and acts as a passive cooler by removing heat from the building [41–44]. Finally, the type of vegetation is crucial [31,45].

3. Technical aspects of green roofs

Castleton et al. indicate that the structure of a green roof includes the vegetation layer, the growing medium (or soil layer), the drainage layer and the membrane layer, which serves as a filter and waterproofing layer [23]. Many other layers are often required, such as the root barrier (generally between the soil layer and the drainage one), the irrigation system (within or above the soil layer) and supplementary filters [46–48].

The development of a green roof can use versatile construction techniques such as a complete system, a modular system or pre-cultivated blankets [15,28,39]. The complete system encompasses the entire roof while the other two are planted before being integrated above the rooftop. A comparison of these systems with a view to their challenges is reported in Table 2.

In regards to the possible vegetation types, Cox states that different plant types could lead varying thermal insulation values [5]. Different plant choices in green roofs lead to significant variations in the thermal insulation value (Fig. 2).

Sedum, one of the most popular types of plants for green roofs, provides high shading against solar radiation, has a short root structure and is compatible with limited water sources [41,42]. However, it is unable to avoid convective heat transfer under its leaves and consequently, it has a low thermal resistance value [41,42]. On the other hand, Ryegrass allows for much air circulation but its potential for shading is limited. Vinca guarantees better shading compared to the others, but it also allows convective heat transfer [6].

Table 2
Design construction classification of green roof systems [15,28,39].

Issue	Pre-cultivated system	Modular system	Complete system
System	Pre-planted	Pre-planted	Layered system
Weight	Low	Average	Generally high
Installation	Simple and fast	Simple and fast	Complex
Maintenance	Simple	Simple	Complex
Cost	Low	Average	High

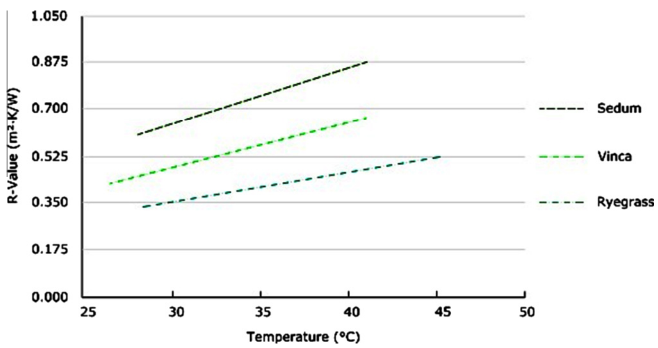


Fig. 2. Thermal resistance of the same green roof with different plants: Sedum, Vinca, and Ryegrass (drawn using data in [5]).

The most important characteristics of the vegetation that influence heat transfer of a green roof are plant height, leaf area index (LAI), fractional coverage, albedo, and stomatal resistance [19,20]. The LAI is a representation of the plan-form area coverage of the leave. Values of LAI depend on plant type, and are typically in the range of 0.5–5.0. The fractional coverage measures the fraction of the roof surface that is directly covered by at least one leaf. This parameter governs the radiative characteristics of the soil media and, although it is related to LAI, it refers to a different concept. The albedo is the reflectivity of the surface to the incident solar energy over the vegetation layer. Lastly, the stomatal resistance is a biophysical parameter that governs the rate at which the plant transpires moisture (the stomata are the intercellular openings between epidermal cells on the leaf surfaces, and their closing and opening rules of transpiration) [19,20].

Simulations in different climates exploring variations in LAI have shown that a high LAI (LAI = 5) corresponds to an increase of energy consumption in winter and a reduction in summer [19,49].

Fig. 3. Plantation alternatives for green roof designs, modified from [57].

Many different alternatives of plantations for green roofs exist (Fig. 3). Köhler and Poll recently offered a complete review of common plants [50]. Comparing many plant types, MacIvor et al. found that the dry land plants have higher thermal resistance than wetland ones [51]. Sutton et al. scrutinized the effectiveness of prairie and grassland species and found that most of the vegetation types can successfully perform once sufficient irrigation and soil layer depth are provided [52]. The study by Schweitzer and Erell [53] argues that despite the confirmed benefits of green roofs in temperate and tropical regions, it is very challenging to use them in extremely hot and dry regions. The respective study has analyzed four different alternatives of plantations including *Aptenia*, *Halimione*, *Sesuvium*, and *Pennisetum*, and has found that *Pennisetum clandestinum* encompassed the most significant positive effect [53].

Durhman recommended to use several species of Sedum, among which "*s. spurius leningrad white, s. acre, s. album bella d inverno, s. midden- dorffianum, s. reflexum, s. sediforme, and s. spurium summer glory. Subsidiary species that are present at specific substrate depths include s. dasyphyllum burnatii, s. dasyphyllum lilac mound, s. diffusum, s. hispanicum, and s. kamtschaticum*" [54]. Getter and Rowe proposed sempervivum and delospermaas for green roofs without irrigation [55]. Various studies proclaimed that the use of diverse type of plantations could be helpful for maximizing the effectiveness of green roofs [43,44]. However, the selection of plant type must be established according to the climatic conditions, the plant impact on the ecosystems [55,56]. Overall, there is a need for research about comparisons among various types of plants to provide design guidelines for selecting the most appropriate plants for a given green roof [55–57]. These researches should consider different possible soil depths, local climates, water availability, and plant density, as there is often a misunderstanding of the impacts of these variables over the environmental of green roofs.

4. Heat transfer in green roofs

Radiative heat forcing from the sun dominates the energy balance of a green roof. The solar radiation is balanced by sensible (convection) and latent (evaporative) heat flux from soil and plant surfaces, combined with conduction of heat into the soil substrate and long-wave (thermal) radiation to and from the soil and leaf surfaces.

Various studies have analyzed the thermal performance of green roofs in different world regions [58,59]. In principle, different phenomena occur in green roofs:

- Soil works as an inertial mass with a high heat thermal capacity, high time lag effect and low dynamic thermal trasmittance.
- Foliage behaves as a shading device under which convection provokes heat thermal exchange, but, foliage absorbs part of the thermal energy for its vital process of photosynthesis.
- Soil and vegetative layers induce evaporative and evapotranspiration cooling.

Green roofs reflect between 20% and 30% of solar radiation, and absorb up to 60% of it through photosynthesis. This means that a percentage below 20% of the heat is transmitted to the growing medium [60]. Weng et al. investigated the correlations between the internal temperatures and the plant varieties and found that vegetation abundance is effective in adjusting land surface temperature [60].

Liu and Minor reported the energy effectiveness of green roofs with a heat flow reduction in a range of 70–90% in summer and 10–30% in winter [61]. Moreover, the thermal influence of green roof was enhanced (by 3% in the summer) once the depth of growing medium was increased and lighter colors were utilized [61].

An interesting evaluation of the effectiveness of green roofs comes by comparing their performance with that of cool roofs (roofs with high albedo). Different studies have shown different results [62,63]. Recently, Sathien et al. compared two test rooms with air conditioning and quantified the decreased thermal losses for the room with the green roof [64], without being able to define if a green roof over performs a cool roof.

Fang focused on the reduction of thermal losses of green roofs and found that the coverage ratio and the leaf thickness are highly contributive to the thermal reduction ratio [65]. For instance, through using *Schefflera arboricola*, 70% coverage ratio and 2.25 mm total leaf thickness could lead to 80% thermal reduction ratio [65]. On the other hand, Qin et al. discussed the ultimate impacts on the temperature variations of green roofs, and proved that green roofs encompass great potential for decreasing the surface temperature (reduction of 7.3 °C) and the ambient air temperature (reduction of 0.5 °C) [66].

A determinant aspect for assessing the thermal performance of a green roof is the thermal resistance of the roof below the vegetation layer: if the green roof is above a well-insulated roof, then the green roof energy balance would be decoupled from that of the building, and the green roof will have an impact mainly on the urban environment. Contrarily, if the green roof is above a less-insulated roof, then its energy balance significantly affects the building. Most of studies treat green roofs similarly to an additional insulation layer with certain inertia. In this regard, importance lies in understanding the different heat fluxes. Fig. 4 shows the main phenomena happening in a green roof. As it is evident, the behavior is complex and the latent heat exchange is a key process.

To estimate the various heat exchange mechanisms in a green roof, it is important to distinguish conductive, convective and evapotranspiration heat exchanges [5].

$$q_{cond} = K \cdot \frac{(T_S - T_C)}{L} \tag{1}$$

$$q_{evap} = m \cdot h_{fg-T_s} \tag{2}$$

$$q_{conv} = h \cdot (T_\infty - T_S) \tag{3}$$

where the meaning of the symbols are in the *legend*. Formula (1)–(3)do not explicit the different phenomena reported in Fig. 4. Sailor proposed a more detailed model that takes into account different design options such as growing layer attributes and plant types [19]. Sailor's model accounts for the radiative exchanges, the effects of vegetation on convective thermal flow, evapotranspiration through soil and vegetation, heat transfer through the ground with change in soil thermo-physical properties and moisture. The energy balances for vegetation (F_f) and ground (F_g) are:

$$F_f = \sigma_f\left[I_S^{\downarrow}(1-\alpha_f) + \varepsilon_f I_{ir}^{\downarrow} - \varepsilon_f \sigma T_f^4\right] + \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1}(T_g^4 - T_f^4) + H_f + L_f \tag{4}$$

$$F_g = (1-\sigma_f)\left[I_S^{\downarrow}(1-\alpha_g) + \varepsilon_g I_{ir}^{\downarrow} - \varepsilon_g \sigma T_g^4\right] - \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1}(T_g^4 - T_f^4) + H_g + L_g + K\frac{\partial T_g}{\partial z} \tag{5}$$

Eq. (4) takes into account the part of solar radiation absorbed by the vegetation, and the sensible (H_f) and latent (L_f) thermal flows. These are:

$$H_f = (1.1 \cdot LAI \rho_{af} C_{p-air} C_f W_{af})(T_{af} - T_f) \tag{6}$$

$$L_f = l_f \cdot LAI \cdot \rho_{af} C_f W_{af} r''(q_{af} - q_{f,sat}) \tag{7}$$

Eq. (5) evaluates the energy balances in the soil. Sailor, recalling models typical of atmosphere modeling communities, reports the sensible (H_g) and latent (L_g) heat exchanges:

$$H_g = (\rho_{ag} C_{p-air} C_{hg} W_{af}(T_{af} - T_g)) \tag{8}$$

$$L_g = C_{e,g} l_g W_{af} \rho_{ag}(q_{af} - q_g) \tag{9}$$

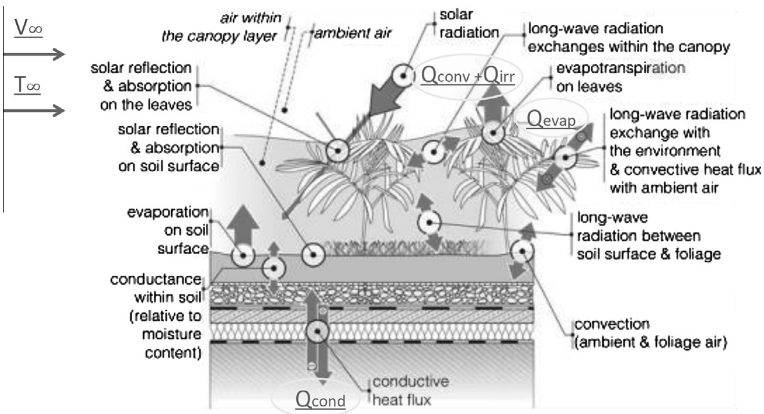


Fig. 4. Heat transfer in green roofs (redesigned from [31]).

Sailor's model facilitates the investigation of design options including growing media thermal properties and depth, and vegetation characteristics such as plant type, height and leaf area indexes. The model was tested successfully using measurements of a green roof in Florida. It was since implemented in the energy simulation software Energy Plus, and it is also available in the common interface Design Builder [19]. Meanwhile, a recent research by Tabares-Velasco et al. has presented a green roof model that allows predicting also the mass transfer in green roofs [8]. Chan recently used the overall thermal transfer value of building with green roofs in order to measure the total average heat gains [67].

More recently, through a collaboration involving Portland State University, University of Toronto, and Green Roofs for Healthy Cities, Sailor developed a web-calculator which allows comparing the annual energy performance of a building with a vegetative green roof to the same building with either a dark roof or a white roof [69]. Nowadays, this calculator allows evaluation of the effect of using a green roof in new and old constructions of office and residential buildings, and considers precipitation and weather data, according to ASHRAE standards. Unfortunately, the web calculator is available only for US cities, whereas a similar tool for other countries would be particularly useful.

5. Environmental benefits of green roofs

Environmental benefits intertwine the types of roofs such as ground depth and vegetation type, and the climate. The following analysis extensively considers both previous aspects. Table 3 assists the analysis of the several benefits.

5.1. Energy consumption reduction

Green roofs are highly efficient in reducing the variation of indoor temperature and decreasing the level of building energy consumption both in warm and cold climates [23,25]. However, the building characteristics play an important role in the possible contribution of green roofs. In non-insulated buildings the impact of green roofs is much higher than in insulated ones, whereas the better the insulation of the roof, the lower the contribution of the green roof. In parallel, the characteristics of the energy load of the building (more cooling or heating load) help understanding the possible contribution of a green roof [25].

Table 3
Environmental benefits of green roofs and main related publications.

Environmental benefits of green roofs	Source
Energy consumption reduction	
Decreasing cooling and heating loads	[18–26,40–42,48,49,58,59,67,74–81]
Improvement of air temperature	[16,18–21,25,65,66,73]
Urban heat island	
Decrease of the urban heat island effect	[5,26,29,58,59,62,63,84–96,100–102]
Reduction of carbon footprints	[26,60,88,97]
Air pollution mitigation	
Enhanced urban air quality	[26–28,32,101,104,109]
Mitigation of air pollution	[20,29,48,100–103,116]
Water management	
Stormwater management	[26,29,33,67–70,110–121,124]
Enhanced water run-off quality	[33,86,124,125]
Improved use of rainwater	[35,48,119]
Enhancement of urban hydrology	[26,116]
Sound absorption	
Sound insulation	[128–131]
Noise absorption	[133,134]
Ecological preservation	
Reduction of habitat lost	[15,26,29,56,136–139]
Biodiversity and improved landscape	[28,38,43,44,53,54,67,140–142,144–146]

In warm climates, green roofs potentially reduce the indoor temperature through shading the rooftop layer and preventing the direct influence of solar radiations [70,71]. Simmons et al. stated that extensive green roofs possess great potential for the climates of subtropical regions with high temperatures and strong rain [72]. A related study found that in Greece green roofs reduce the energy utilized for cooling between 2% and 48% depending on the area covered by the green roof with an indoor temperature reduction up to 4 K [73]. Many studies in warm climate revealed the importance of the climate characteristics, and in particular, of the low level of rainfall over night cooling [31]. In a recent study in Singapore, the temperature variations of a typical roof and a green roof were investigated (Fig. 5) [66]. The analysis showed the positive impact of green roofs on decreasing the variation of the surface temperature with respect to the air temperature (Fig. 5a), and stabilizing the temperature at different levels in the soil (Fig. 5b).

According to Jim, who analyzed the effectiveness of green roofs in the warm and humid climate of Hong Kong (comparing three plantations including grass, groundcover herb and shrub), the type of plantation in green roofs plays a notable role in cooling effects [74] (Fig. 6). The results demonstrate the importance of the plant form, type, and biomass structure towards cooling potential. Referring to the observed variations in temperature at different levels, the study concludes that biomass quantity and complexity are the most influential factors over effectiveness for the energy saving [74].

A recent study by Olivieri et al. in Mediterranean coastal climate in summer found that once the density of plants in a green roof is increased, although the roof structure substantially insulated (*U*-Value: 0.24 W/m^2 K), the green roof reduced cooling consumption of 60% in comparison to a conventional roof [75].

The benefits of green roofs in cold climates are globally acknowledged, although some authors have found that the insulation of the roof, besides the green roof structure, may have negative effect [18]. In a detailed study in Canada, Liu and Baskaran showed that the daily surface temperature variation with a green roof was approximately 6 °C compared to a variation of 45 °C in a typical roof [16]. Based on the application of a green roof, the heat gain in summer decreased whereas the reduction of the heat loss in winter was found to be advantageous.

In another study performed in the Midwestern of U.S., with hot and humid summers, and cold and snowy winters, researchers found that the impacts on the surface temperature and the heat flux are highly significant in summer (167% on average) compared to the winter (13% on average) [76]. The capability of green roofs in decreasing the heat flux in winter and summer is illustrated in Figs. 7 and 8 respectively.

Likewise, the respective study recommends increasing the depth of growing medium layer and providing irrigation supplies for increasing evapotranspiration. Zhao showed that green roofs also decrease the heat flow in extreme climates such as in snowy winters [77].

Recently, several studies have looked at the same green roof in different climates to explore advantages and disadvantages of the same structure. Sun et al. considered two case studies located at Princeton University in US and Tsinghua University in China, confirming the effectiveness of green roofs in both locations in reducing the surface temperature and heat losses [35].

Pandey et al. analyzed the cooling effects of green roofs in China based on a comparison between two rooms with different rooftop structures (green roof versus bare reinforced cement concrete

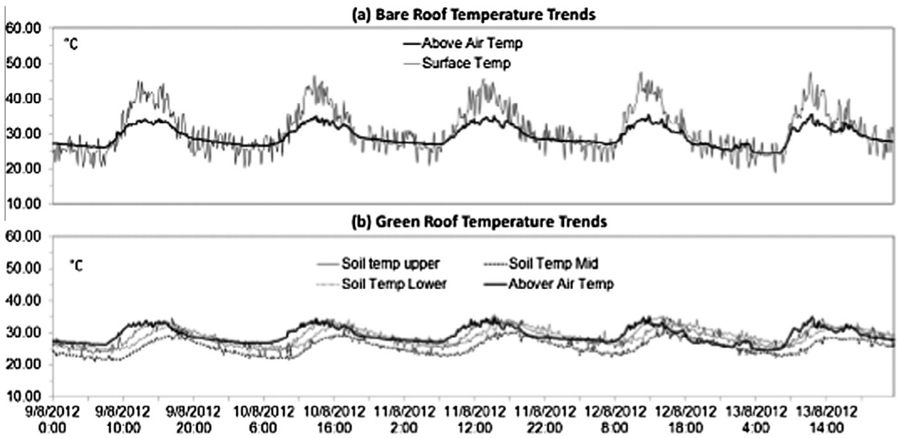


Fig. 5. The temperature variations of bare (a) and a green roof (b) in Singapore over five summer days [66].

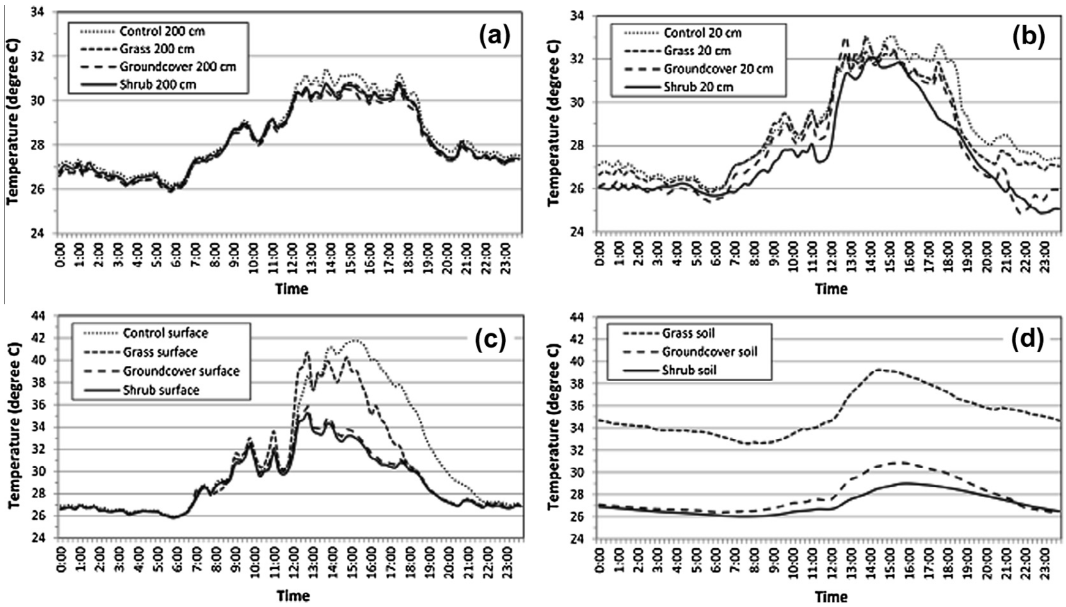


Fig. 6. Comparison of diurnal temperature patterns on a typical sunny summer day (4 July 2009) for a control roof (typical) and the three green-roof types (grass, groundcover and shrub): (a) air temperature at 200 cm high, (b) air temperature at 20 cm high, (c) infrared surface temperature, and (d) soil temperature [74].

slab), and concluded that the utilization of green roofs decreased the temperature fluctuations and heat flow through the roof [78]. Table 4 reports the relatively lower temperature of the room integrated with green roof.

Similarly, Spala et al. demonstrated that the integration of green roofs in buildings contributes to energy saving purposes in different Greek cities [79]. However, the respective findings showed that green roofs significantly decreased the cooling loads while their influences on the reduction of heating loads, considering the heating degree days of that country, was marginal. Furthermore, Nardini et al. measured the reduction of the thermal loads through the utilization of different plants in green roofs [80]. This study showed that the substrate depth has a substantial impact on decreasing the thermal load, whereas substrate water content plays a minor role [80].

From a lifecycle analysis point of view, a recent study evaluated the outcome of a green roof and a white roof for houses in St. Louis, MO, in a 10-year period [81]. The results indicate that the green roof causes more embodied energy in comparison to the white roof. Nonetheless, despite the higher consumed level of energy for green roof maintenance, the house integrated with green roof shows comparatively lower level of energy consumption than the house with white roof [81].

Sailor et al. performed a comparison of energy performance in four U.S. cities, Houston, New York City, Phoenix and Portland, and showed that the energy performance of green roof resulted particularly improved by increases in the plantation density in every city [82].

Key findings derived from the analysis of green roofs with view to the energy consumption reduction purposes are summarized in Table 5.

5.2. Urban heat island effect

Urban growth, especially in developed countries, has resulted in various negative environmental consequences, such as the accelerated rate of increased air pollution, urban heat island (UHI) effect and loss of habitats [9,83]. In this regard, green roofs may contribute to solve these concerns, as their use is not only beneficial at building-scale but it embraces many fundamental benefits at city-scale too [84]. One of these benefits is the possibility to mitigate the urban heat island effect [85–88].

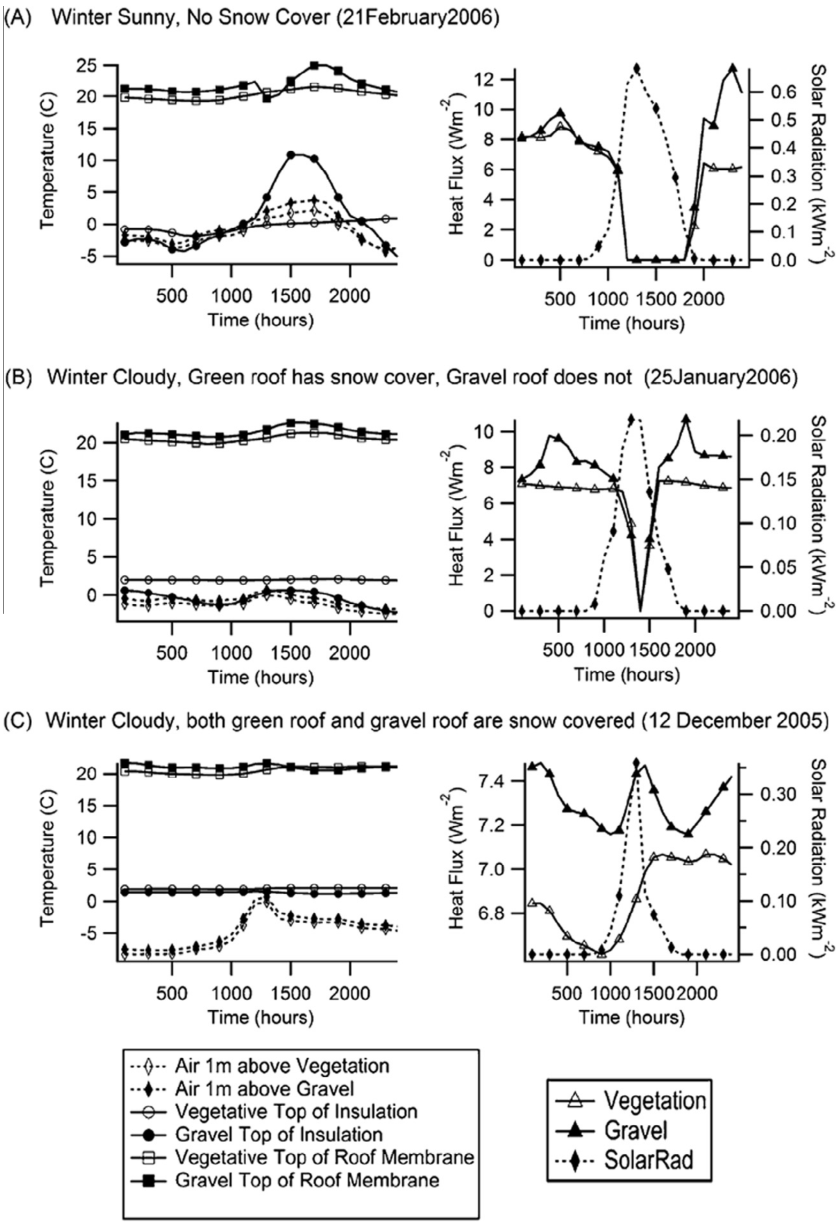


Fig. 7. Temperature and heat flux in one-day for various environmental conditions during winter: (A) winter sunny, no snow cover; (B) winter cloudy, only green roof has snow cover; (C) winter cloudy, both green roof and gravel roof are snow covered. Negative and positive heat flux readings represent heat entering and leaving the building, respectively [76].

The albedo of green roofs ranges from 0.7 to 0.85, a value much higher than the albedo of bitumen, tar, and gravel roofs (typically from 0.1 to 0.2). Gill et al. showed that an increase by 10% of the urban green in Manchester, UK, could avoid the predicted increase of 4 K of the ambient temperature over the next 80 years [85].

Santamouris recently reviewed several mitigation technologies to fight UHI effect and remarks that the large-scale application of green roofs could reduce the ambient temperature from 0.3 °C to 3 °C [63]. Moreover, by comparing cool and green roofs, he concluded that for UHI mitigation, cool roofs are generally more effective in a sunny climatic condition, than green roofs, whereas green roof should be preferable in moderate climatic conditions [63]. Considered the complexity of this topic, readers are encouraged to look at the previous paper for a more complete discussion of current knowledge.

Various studies discussed the possible influence of green roofs in urban sustainability reducing the UHI effect [86–88]. Findings indicate that the highest impact of green roofs occurs in the hottest and driest climates (Fig. 9). Comparing different cities, Alexandri and Jones conclude that Riyadh, situated in a hot and dry region, would receive the largest temperature mitigation from the use of green roofs [84].

The findings of a similar study show that the highest level of contribution of green roofs to the cooling purposes was observed during the night, and was 1.58 °C [89]. This study investigated the UHI mitigation in comparison to a typical concrete roof and confirmed that the monthly temperature above the green roof was 1.06 °C lower.

Similarly, concentrating on the macroscale, Susca et al. concluded that a maximum reduction rate of 2 °C in New York is possible [90].

The extensive implementation of green roofs for mitigating the UHI effect needs a proper analysis of the geometrical configuration of the city. Wong et al. have analyzed the issue of over-shading, which may occur in high-density cities, such as Hong Kong [91]. Their simulations showed that half of the area could not receive di-

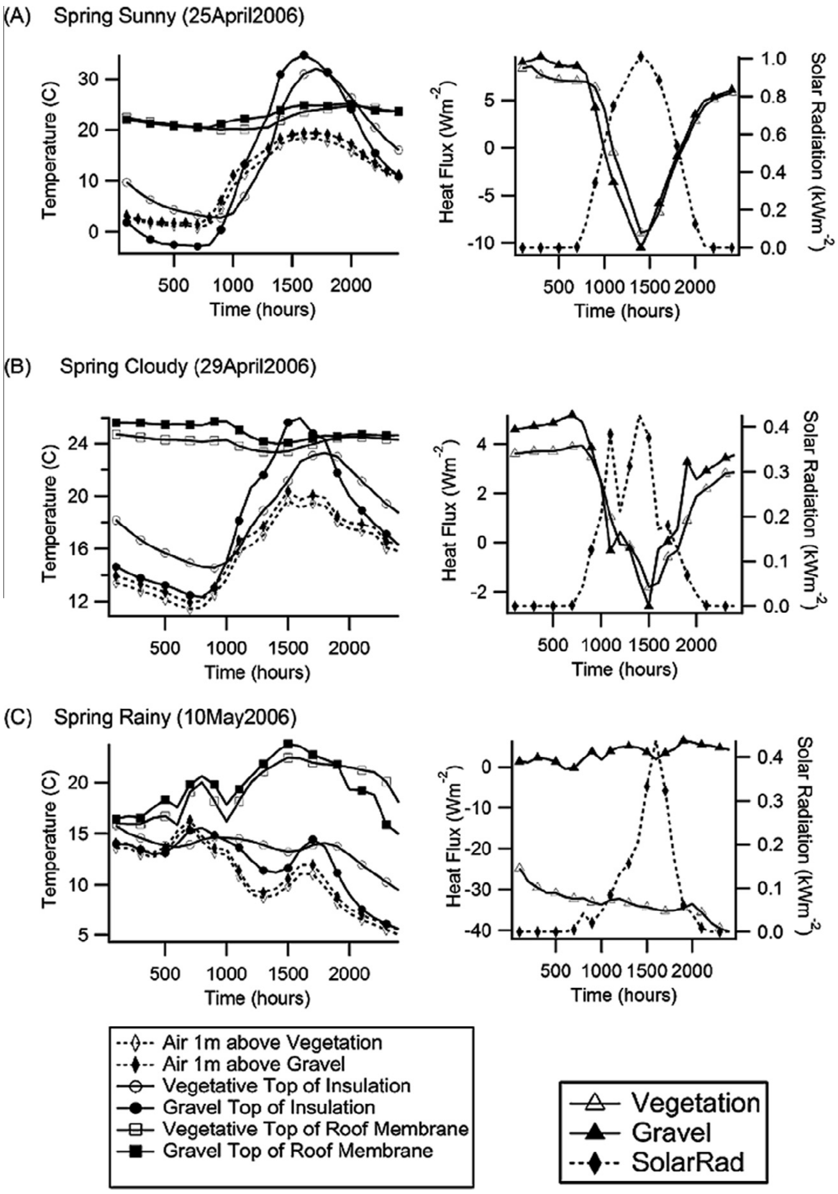


Fig. 8. Temperature and heat flux in one-day period during summer: (A) summer sunny; (B) summer cloudy; (C) summer rainy. Negative and positive heat flux readings represent heat entering and leaving the building, respectively [76].

Table 4
Comparison of green roof versus bare reinforced cement concrete (RCC) slab temperature in a hot summer day for outdoor ambient and indoor ambient in two rooms (DBT is the dry bulb temperature and WBT is the wet bulb temperature) [78].

Time	Outside air temperature		Room temperature with the bare RCC slab over the roof		Room temperature with a roof garden over the roof	
	DBT	WBT	DBT	WBT	DBT	WBT
8.00 a.m.	24.4	22.2	21.28	19.18	17.88	15.65
9.00 a.m.	30.2	28	27.08	24.98	23.27	21.04
10.00 a.m.	31.6	29.4	28.48	26.38	25.28	23.05
11.00 a.m.	33.7	31.5	30.58	28.48	26.48	24.25
12.00 a.m.	35.2	33	32.08	29.98	27.98	25.75
1.00 p.m.	38.3	36.1	35.18	33.08	31.08	28.85
2.00 p.m.	40.9	38.7	37.78	35.68	33.68	31.45
3.00 p.m.	40.6	38.4	37.48	35.38	33.38	31.15
4.00 p.m.	36.1	33.9	32.98	30.88	28.88	26.65
5.00 p.m.	34.2	32	31.08	28.98	26.98	24.75
6.00 p.m.	31.8	29.6	28.68	26.58	24.58	22.35
Average	34.2727	32.0727	31.1527	29.0527	27.2245	24.9945

Table 5
Comparison of energy consumption reduction in different climatic conditions and main related publications.

Climatic conditions	Remarks for energy consumption reduction	Key references
Warm climates (or warm summer)	Shading the rooftop layer and preventing the direct influence of solar radiations	[66,69–71,75,76,79,83]
	Decreasing the variation of the surface and indoor temperature, stabilizing the temperature Reducing peaks of indoor air temperature Reducing energy used for cooling purpose	
Warm and humid climate	Daily temperature variations largely depend on the soil depths	[13,40,74,83]
Warm and dry climates	Effectively reduce the outdoor air temperature and cooling the indoor ambient temperature	[132]
Subtropical climates	Great potentials for reducing the high temperature	[7,72]
Cold climates (cold and snowy winters)	Reduction of daily temperature variation Reducing the heat flow Impacts on the surface temperature and the heat flux Decreasing the heat flow Doubtful energy performance for green roofs in winter (both positive and negative impact on energy consumption are reported)	[16,61,77,83]

rect sunlight in the period of winter-spring and 5.8% of the total roof zone was deeply compromised due to over-shading phenomenon especially during the winter [91].

Smith and Roeber focused on the possible effect of green roofs on the UHI in Chicago and concluded that the urban temperature from 7 to 11 pm could decrease with the range of 2 K or 3 K [92]. A similar study by Savio et al. in New York, reports that the temperature at 2 m height decreased between 0.37 and 0.86 K whereas, the daily average temperature reduction rate between 0.3 and 0.55 K [93]. Simulations in Japan and China claim that the reduction impacts on urban temperature are minor [94,95].

A recent trend in this field is the analysis of different green roofs in various solar radiation intensities to measure the latent heat releases. Takebayashi and Moriyama conclude that green roofs subjected to a peak solar radiation intensity of 900 W/m^2 could result in 300–400 W/m^2 latent heat release [62]. Lazzarin et al. claim that in the same solar radiation intensity, dry roof and wet roofs result in 110 and 230 W/m^2 latent heat release respectively [96]. On the other hand, Feng et al. report 600 W/m^2 of latent heat release upon the use of extensive green roofs [97]. Meanwhile, Rezaei and Berghaghe et al. represent that in solar radiation intensity of 1000 W/m^2, shrubs result in 150 W/m^2 while grass result in 100 W/m^2 latent heat release [98,99]. To conclude, it is evident that green roofs significantly contribute to the latent heat release, while the variations in the findings and the calculated values show the need for future. On average a reduction of 2 °C finally been found, but following the recent review by Santamouris, an interval between 0.3 and 3 should be expected [63].

A comparison of key findings derived from the analysis of green roofs with view to the UHI mitigations is reported in Table 6.

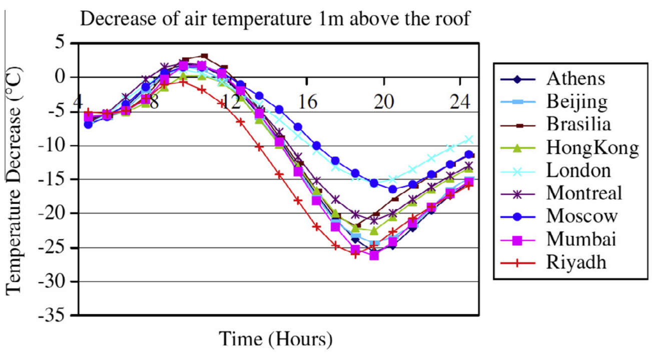


Fig. 9. Air temperature decrease at 1 m above the roof during a hot day once green roofs are extensively implemented in different cities worldwide [84].

5.3. Air pollution mitigation

Intensive green roofs have often been considered able to reduce air pollution. In fact, growing plants on rooftops partially substitutes the vegetation demolished during construction.

Currie and Bass revealed that trees are the most influential plants for reducing air pollution [104]. They modeled the effectiveness in reducing the air pollution based on an urban forest effect model in Chicago and Detroit, and found that 109 ha of green roofs would contribute to 7.87 metric tons of air pollution removal per year [117]. Similarly, Deutsch et al. utilized an urban forest effect model for Washington DC and confirmed the potential of green roofs for pollution removal [105]. Likewise, Yang and Bass presented promising results of experimental research for air pollution mitigation in Chicago. The potential of green roofs for reducing the air pollution of NO_x, SO_2 and PM_{10} is reported by Speak et al. [106]. Similarly, Tan and Sia investigated the level of air pollutions (in particular, sulfur dioxide) before and after integrating green roofs in Singapore: the findings reveal up to 37% pollution removal upon extensively utilizing green roofs [107].

Another possible way to assess the benefits of green roofs on air pollution mitigation is by evaluating their capability towards energy saving of building and UHI reduction. As UHI increases radiant temperature and cooling loads of buildings, thus, the effectiveness of green roofs in reducing the heat island will indirectly result in reducing UHI [63]. Many studies evaluated how the decrease of energy consumption through green roofs would reduce the level of pollution indirectly [108,109].

A comparison of key findings derived from the analysis of green roofs with consideration to air pollution mitigation is reported in Table 7.

5.4. Water management

Many authors indicate the reduction of storm water runoff as the most important environmental benefits of green roofs [110,103]. Several others emphasized the role of water availability in the design of green roofs and its roof plants, and often focused on plant types in conditions with low water availability [29,43,114]. The roof slope influences the level of runoff retention potential and has also received increasing attention [111,115].

DeNardo et al. and VanWoert et al. showed that green roofs could lead to 60% runoff mitigation for extensive green roofs and up to 100% for intensive green roofs [116]. Lower values, in the range between 25% and 50%, were found in other researches [117–119]. VanWoert et al. compared the level of stormwater retention for three different roof structures including a conven-

Table 6
Comparison of urban heat island mitigation effect obtained in different types of study and main related publications.

Type of study	Concluding remarks for UHI reduction	Key references
Experimental observation	Reduction of temperature by 1.5–2 °C on average, with higher impact in the hottest and driest climates	[85–88]
	Large-scale application of green roofs could reduce the ambient temperature from 0.3 °C to 3 °C	[63]
	Macro-scale application of green roofs could lead to the mitigation of the urban heat island effect and a maximum reduction rate of 2 °C	[90,91]

Table 7
Comparison of air pollution mitigation in different types of study and main related publications.

Type of study	Remarks for air pollution mitigation	Key references
Case study	Green roofs indirectly reduce air pollution by reducing the urban heat island effect and the building energy consumption	[101–108]
	Trees are the most effective plants in removing NO_x, SO_2 and PM_{10}	[100]
	109 ha of green roofs contribute to 7.87 metric-tons of air pollution removal per year	[104]
Analysis based on UFORE model	Up to 37% pollution removal upon extensively utilizing green roofs	[107]

tional roof, an extensive green roof without plantation and an extensive green roof with plantation [117]. As a result, the level of stormwater retention was improved by 82.8% for the extensive green roof [117]. A recent study has compared three types of roofs including a conventional roof, a traditional green roof and an extensive green roof integrated with drainage system [120]. The results show that the traditional green roof has the potential to decrease the peak runoff to 57% while the extensive green roof encompasses a 71.7% potential reduction of the peak runoff. Recent research by Mickovski et al. [121] compared the effects of green roofs with respect to surface runoff for three types of vegetation (long grass, short grass and Sedum) as illustrated in Fig. 10. The findings show that Sedum encompasses the lowest impact on surface runoff volume [121].

According to Roehr and Kong, comparing three case studies in Vancouver, Kelowna (Canada), and Shanghai, a yearly runoff reduction of 29%, 55% and 100% was observed respectively [122].

The impact of green roofs towards storm water runoff also has considerable effects on the water run-off quality [123]. Compared to traditional roofs, intensive green roofs reduce runoff concentrations of lead by a factor of 3, zinc by a factor of 1.5, cadmium by a factor of 2.5, and copper by a factor of 3 [86]. However, Vijayaraghavan et al. showed that the specific nature of runoff quality from green roofs is highly dependent on the green roof components and nutrient concentrations in runoff decrease in time after installation [124]. Moreover, there are questions regarding the impact that green roofs have on phosphorus content of the water [33,125]. For example, Vijayaraghavan et al. showed that concentrations of phosphate and nitrate from green roof can be high [124].

A recent research at the Worcester Polytechnic Institute (MA, USA) has investigated the quality of water runoff. Comparisons of grab samples of stormwater from a green and a non-green roof within the first few seasons following installation confirmed that phosphorus was leaching into the runoff of the green roof. Additional experiments with simulated rainfall confirmed that complex biogeochemical processes between the water, vegetation and soil matrix affect. However, while many green roofs have been found to leach phosphorus into stormwater runoff within the first few years after installation, it is normally assumed that this phenomenon will not continue after the green roof vegetation has been established phosphorus and other constituent concentrations in the runoff [126,127]. Further research regarding the role of green roofs in water management is necessary for ensuring a consistency in the findings.

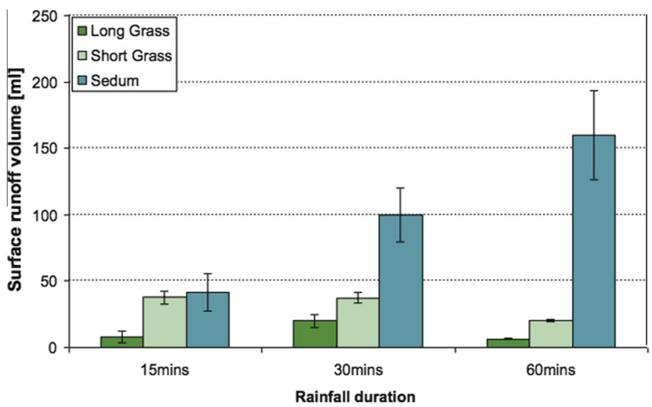


Fig. 10. Experimental comparison of surface runoff volume in different green roofs for different rainfall duration [121].

To conclude, key findings derived from the analysis of green roofs with view to the role of water management are reported in Table 8.

5.5. Sound insulation and noise reduction

Green roofs have often been proposed for their potential related to sound absorption and noise insulation [128–132]. Referring to the transmission loss (TL) as the extent of sound level decreased through partitions, an empirical analysis concluded that green roofs increase TL from 5 to 13 dB at low and mid frequencies, and from 2 dB to 8 dB at high frequencies [131].

A recent study has measured the sound transmission loss of a reference roof (conventional type) and two green roofs [132]. These were identical with the only difference in the depth size of substrate (75 mm for GR1 and 150 mm for GR2). The analysis revealed that the increase of TL through GR1 at different frequencies was less consistent while the respective increase of TL through GR2 was more reliable. The findings also demonstrate that deep green roof increased the transmission loss from 5 dB to 13 dB at low and mid frequency bands (50–2000 Hz), and of less than 6 dB at higher frequencies [132].

Additionally, with focus on urban scale, based on the experiments of Yang et al. and Connelly et al., it is proven that green roofs considerably decrease the noises at street level in urban areas

Table 8
Remarks of water management according study and main related publications.

Type of study	Remarks for water management	Key references
Experimental measurement	Reduction of storm water runoff varies between 60% and 100%	[111–116]
	Decreasing the slope and increasing the depth of growing layer is highly promising for runoff reduction	[117]
Experimental measurement and climatological model	Important relationships (and issues) exist between green roof type and water quality	[124,33,125–127]

Table 9
Substances needed and released due to the production process of non-recycled (above) and recycled polymers (below) [38].

LDPE				PP			
Substance	Media	Unit	Amount released	Substance	Media	Unit	Amount released
Radon-222	Air	Bq	298	Radon-222	Air	Bq	198
Noble gases, radioactive, unspecified	Air	Bq	134	Noble gases, radioactive, unspecified	Air	Bq	91
Heat, waste	Air	MJ	27	Heat, waste	Air	MJ	21
Hydrogen-3, Tritium	Water	Bq	6	Hydrogen-3, Tritium	Water	Bq	4
Carbon dioxide, Fossil	Air	kg	2	Carbon dioxide, Fossil	Air	kg	1.7
Energy, potential (in hydropower reservoir), converted	Raw (input)	MJ	0.9	Oil, crude, in ground	Raw (input)	kg	1
Oil, crude, in ground	Raw (input)	kg	0.9	Gas, natural, in ground	Raw (input)	m^3	0.6
Gas, natural, in ground	Raw (input)	m^3	0.8	Energy, potential (in hydropower reservoir), converted	Raw (input)	MJ	0.30
Energy, gross calorific value, in biomass	Raw (input)	MJ	0.4	Energy, gross calorific value, in biomass	Raw (input)	MJ	0.2
Coal, hard, unspecified, in ground	Raw (input)	kg	0.1	Coal, hard, unspecified, in ground	Raw (input)	kg	0.08
Radioactive species	Air	Bq	3,639,724	Additives	Raw (input)	kg	3,763,977
Radioactive species	Water	Bq	33,441	Scandium	Air	kg	3,729,724
Radon-222	Air	Bq	297	Acids	Raw (input)	kg	317
Noble gases, radioactive, unspecified	Air	Bq	133	Waste in bioactive landfill	Solid waste	kg	21
Heat, waste	Air	MJ	27	Phosphate	Water	kg	1.8
Hydrogen-3, Tritium	Water	Bq	6	Formaldehyde	Air	kg	0.50
Energy, potential (in hydropower reservoir), converted	Raw (input)	MJ	3.5	Fluoride	Air	kg	0.40
Carbon dioxide, Fossil	Air	kg	2	Boron	Water	kg	0.10
Oil, crude, in ground	Raw (input)	kg	0.9	Hydrocarbons, aliphatic, unsaturated	Air	kg	0.08
Gas, natural, in ground	Raw (input)	m^3	0.8	Glyphosate	Soil	kg	0.05

thanks to the high absorption coefficient of the vegetation layer [133,134]. This benefit is more evident in green roofs above low buildings, because the vegetation layer should be exposed to the direct urban sound field to be an effective absorptive surface.

5.6. Ecological preservation

Various studies indicate benefits of green roofs related to environmental quality enhancement and ecological preservation [26,103]. Peng and Jim [135] highlight the important role of large-scale green roofs in urban ecology, but describe the difficulty of measurement methods of these benefits. Bianchini and Hewage propose the use of life-cycle analyses to show the environmental benefits of green roofs by comparing emissions of NO_2, SO_2, O_3 and PM_{10} in green roof material manufacturing process, such as polymers, with the green roof's pollution removal capacity. The analysis demonstrated that green roofs are sustainable products in long-term basis. In general, air pollution due to the polymer production process can be balanced by green roofs in 13 years [136]. Various studies have focused on the impact of green roofs towards enhancing the biodiversity and reduction of habitat losses [136–143].

Recently, the concept that green roofs has often been associated to the enhancement of urban agriculture, especially vegetable production [144,145]. Chen stresses the public impact of green roofs utilization for the creation of urban gardens [26].

Green roofs have been criticized for the adoption of bitumen layers in their structures. On this regard, the water resistance layer is generally accused not to be an eco-friendly material. In this regard, the study by Bianchini and Hewage performed a lifecycle analysis comparison between two polymer materials used in green roofs as recycled low-density polyethylene (LDPE) and non-recycled low-density polyethylene (LDPE) was done [136]. The findings explicitly show that the use of recycled type leads to 2.8 times less toxic substances to air. Likewise, it is inferred that the toxic concentration of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3) and particulate matter (PM_{10}) derived from the use of non-recycled LDPE are comparatively greater than those released by recycled type, as reported in Table 9 [38].

Existing researches done through a life cycle analyses of green roofs found that extensive green roofs corresponds to lower level of toxic substances than intensive ones. However, intensive roofs usually have bigger plants and higher air dilution rates. In conclusion, the pollution from the production process of the green roof's

Table 10
Annual money saving and simple payback period for different roofing solutions in various European climates [49].

Annual money saving and simple payback period for different roofing solutions												
	Tenerife		Sevilla		Rome		Amsterdam		London		Oslo	
	Annual saving (€)	Simple payback (year)	Annual saving (€)	Simple payback (year)	Annual saving (€)	Simple payback (year)	Annual saving (€)	Simple payback (year)	Annual saving (€)	Simple payback (year)	Annual saving (€)	Simple payback (year)
Traditional	–	–	–	–	–	–	–	–	–	–	–	–
Cool roof	2330	8.5	1736	11.4	1494	13.2	373	52.9	410	48.1	310	63.7
Sedum short	−1296	Negative	−951	Negative	−350	Negative	161	488.8	22	>500	333	236.8
Sedum tall	− 670	Negative	−267	Negative	−28	Negative	−56	Negative	3	>500	551	143.2
Grass lawn	−772	Negative	−163	Negative	−47	Negative	71	>500	53	>500	529	185.5
Short gramineous	−594	Negative	−133	Negative	9	>500	1	>500	6	>500	505	146.4
Tall gramineous	−393	Negative	31	>500	18	>500	−363	Negative	−170	Negative	528	140.1

polymers are generally balanced by green roofs benefits in the long term.

Experiments to explore the use of rubber crumbs in green roofs as drainage layer are getting momentum. Rubber crumbs could save a big amount of energy in comparison to the use of current commercial materials due to the difference in energy need of the transformation process and could provide a solution to the problem of disposing waste tires [147].

6. From Economic Feasibility To Incentivizing Policies

6.1. Economic feasibility and lifecycle cost analysis

Various studies have discussed the economic benefits of green roofs through lifecycle cost analysis, [27,148,149]. The economic feasibility of green roofs is particularly influenced by the selected green roof systems, and in particular, by the type of plants. For example, the life extension of waterproofing layers through the application of green roofs is often sufficient to ensure the economic feasibility of green roofs. In fact, if the waterproofing layer of a normal roof approximately lasts between 10 and 20 years, green roofs could ensure a life beyond 50 years [27,31,70].

One of the economic barrier to the adoption of green roofs comes from the fact that most of the benefits of a green roof are restricted to the highest level [31]. Wong et al. showed that using a life cycle evaluation the cost of an extensive green roof in Singapore resulted in 14.6% lower than of a traditional roof [82]. Findings of another study indicate that correctly designed green roofs are generally economically feasible [48]. However, a barrier is often the lack of rainfalls, as for example in Southern European cities [49]; on the contrary, in Northern Europe (Amsterdam, London, and Oslo), the abundance of rainfall implies satisfactory performance by the different vegetation typologies (Table 10).

The low adoption of green roofs in many countries has hence been related to the lack of economy of scale and expertise [148,151].

All previous analysis only considered energy saving and construction costs without evaluating the many other benefits (air pollution reduction, ecosystem conservation, water management, noise reduction) which are difficult to quantify. A preliminary lifecycle cost analysis expanded to consider the level of environmental impacts of development, creation, integration, and maintenance is reported in [86].

If the feasibility of green roof in new buildings has shown contrasting results, retrofitting existing buildings with green roofs is more often a successful strategy with many economical benefits [23]. This conclusion results from the common low insulation of old buildings and the convenience in increasing the thermal resistance with a green roof. In retrofitting the existing buildings with green roofs, the issue of increase of dead loads and structural failure is often perceived as an obstacle. However, for buildings with reinforced concrete slab or profiled steel decking, additional structural modifications are not needed as these structures can withstand 5–10 kN/m^2 of dead load, which is adequate to support a green roof with a growing medium up to 80 cm [23].

A summary of the economic benefits and barriers of green roofs is reported in Table 11.

6.2. Policies for green roofs

Considering the high-energy consumption and environmental of buildings, many policies worldwide are encouraging more sustainable buildings and often through the application of green roofs [152–155]. These policies generally consists in financial incentives or in reduced storm water or propriety fees. Ecological compensation in terms of density bonus are often promoted. These guarantee the possibility of exceeding the footprint area of the surface area and/or the number of stories allowed if a certain environmental equalization of green roof is included.

A law in Tokyo requires the installation of green roofs in private buildings with built areas larger than 1000 m^2 and in public buildings with built areas larger than 250 m^2, while integrated green roofs must encompass not less than 20% of the whole rooftop area [156]. Germany is supporting the construction of 13.5 million m^2 of green roofs per year [29]. For instance, in Esslingen, 50% of the cost of green roofs is paid back, while in Darmstadt, users can receive a maximum of € 5000 for a green roof. In the cities of Bonn, Cologne and Mannheim, the allocated stormwater fees are considerably reduced once new green roofs are built. Similar policies have been implemented in other countries such as Switzerland and Austria. In Basel, users are repaid 20% of the cost of a green roof [156]. In Toronto, there have been specific policies to promote green roofs in buildings with the ratio of 50–70% of the entire building coverage. In Quebec, an economic incentive is provided per square meter implemented of green roofs [157]. In the U.S., some states have established specific policies, especially in highly urbanized area. For instance, in Oregon, 70% of the roofs of Portland are going to be covered with a green roof [157]. However, most of the policies have been implemented at the city level. Table 11 reports a list of current policies.

Finally, green roofs are often seen as an opportunity for supporting the process of receiving sustainability labels, such as LEED or BREEAM [1,158,159]: this indirect policy, which comes from the sustainable building assessment movement, promises to be fundamental for the diffusion of green roofs.

Table 11
Economic benefits and barriers of green roofs and list of a few policies promoted to overcome these lasts (*the list of policies does not pretend to be exhaustive of all the policies promoted worldwide, it has a bias for United States policies and it aims only to constitute a reference and it*) [10,11,70,74,148–151].

Economic benefits	Economic barriers
Reduce energy consumption	High construction cost
Increase thermal insulation in retrofitting	High maintenance cost, especially with intensive green roofs or when irrigation is needed
Reduce maintenance costs of roof due to lengthening life	Complexity of construction
Reduce costs of water rain off and urban infrastructure	Risks of failure
Improve market and price of the buildings	Expensive integration in existing buildings if adjustments to the structure are needed
Increase usable surface of the building	
Examples of policies for the promotion of green roofs	
Germany	Munich: obligation to landscape all suitable flat roofs with a surface area >100 m^2 Esslingen: 50% of the cost of green roofs is paid back Darmstadt: owners receive up to € 5000 for planting a green roof
Denmark	Copenhagen: all new roofs with a roof pitch under 30° have to be landscaped, providing there is no structural engineering reason preventing it
Canada	Toronto: green roofs are required for all new development above 200 sq/m. Coverage requirement ranges from 20% to 60% of the available roof space Vancouver, BC: all new commercial and industrial buildings over 5000 square meters must have a green roof and the developer will be exempt from development permit fees
United States	Austin, TX: Green Roof Density Bonus gives a density bonus of up to 8 sq/ft for 1 sq/ft of green roof Chicago, IL: The City of Chicago offers up to 50% of cost or $100,000 for development of green roofs covering 50% or more of a rooftop space Baltimora, MA: Stormwater Management Tax Credit is 10% of the cost for the new stormwater management techniques (maximum amount $10,000) Milwaukee, WI: Milwaukee Metropolitan Sewerage District Initiative is provides $5 per sq/ft as incentive to increase green roof coverage Minneapolis, MN: any building that improves stormwater management through green roofs receives a 50% credit in the stormwater fees Nashville, TN: is promoting the installation of green roofs by providing a $10 reduction in a property's sewer fees for every square foot of green roof New York City, NY: gives a one year tax credit of up to $100,000 (or $4.5 per sq/ft) for green roofs that encompass at least 50% of available roof space Philadelphia, PA: offers a credit against the Business Privilege Tax, of 25% of all costs incurred to construct a green roof up to $100,000 Portland, OR: Through the FAR Bonus, the city offers a Floor Area Ratio bonus in its building code (extra 3 sq/ft per foot of green roof may be constructed without additional permits). A grant reimbursement of up to $5 per sq/ft for reducing stormwater infrastructure with a green roof is possible Seattle, WA: the city offers a Floor Area Ratio bonus of extra 3 sq/ft per foot of green roof Washington, DC: The District's green roof rebate program funds $5 per sq/ft of green roof

7. Conclusions

This paper moved from the growing interest in the use of green roofs and the diverse list of journals that focused on them. Reviewing recently published scholarly studies, this paper has analyzed the benefits related to the implementations of green roofs. Findings confirm that green roofs encompass many benefits in terms of environmental sustainability.

The analysis ascertains that each layer and constituent of a green roof has a significant influence over the performance of a green roof. It is also identified that the physical characteristics of buildings including height, number of stories, roof design, and materials influence the performance of green roofs. This highly depends on the roof insulation and the climatic conditions. Identified environmental benefits include decreasing the level of energy consumption, decreasing the urban heat island, mitigating air pollution, enhancing urban air quality, enhancing water run-off quality and stormwater management, reducing noise and increasing biodiversity.

It was also found that the environmental benefits of green roofs are not only limited to the new buildings, as green roofs are promising for retrofitting projects. Better performances of green roofs are in buildings without a proper insulation, more than in highly insulated new buildings. With respect to the energy performance of green roofs, different performances were identified in different seasons/climates. Different perspectives and perceptions (positive and negative) towards the performance of green roofs in winters or cold climate (or whenever the coupling of the green building with the building increases the envelope thermal capacity more than ideally) are reported.

This study has placed high emphasis on the enhancement of water management and reduction of air pollution resulting from the adoption of green roofs.

The review also provided a review of insights about the economic feasibility of green roofs, elucidating their undeniable benefits. Many analysts claim that the use of green roofs is an efficient approach towards sustainable buildings. The findings encourage scientists and researchers to concentrate on the further quantification and analytical assessment of the benefits by using cross-disciplinary approaches with joint analysis of aspects including landscape, plantations, construction, and civil, environmental and mechanical engineering. More studies about vegetation and plants in relation to the characteristics of the climate should be encouraged. Investigating the preferences of users for ensuring the effectiveness of green roofs with a view to the social side could also be the focus of future studies. Likewise, s studies with a focus on the application of green roofs in developing countries and vernacular buildings are needed. Meanwhile, research is necessary to evaluate possible policies for encouraging the use of green roofs. Finally, ways to assess easily the economic impacts of green roofs (such as through online calculators) should be encouraged.

References

[1] Berardi U. Sustainability assessment in the construction sector: rating systems and rated buildings. Sustain Dev 2012;20(6):411–24.
[2] Zhou Y, Clarke L, Eom J, Kyle P, Patel P, Kim S, et al. Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. Appl Energy 2014;113:1077–88.
[3] GhaffarianHoseini A, GhaffarianHoseini A, Dahlan N, Berardi U, Makaremi N. Sustainable energy performances of green buildings: a review of current theories, implementations and challenges. Renew Sustain Energy Rev 2013;25:1–17.
[4] Coutts A, Daly E, Beringer J, Tapper NJ. Assessing practical measures to reduce urban heat: Green and cool roofs. Build Environ 2013;70:266–76.
[5] Cox BK. The influence of ambient temperature on green Roof R-values. Master Thesis. Portland State University; 2010.
[6] Parizotto S, Lamberts R. Investigations of green roof thermal performance in temperate climate: a case study of an experimental building in Florianopolis city, Southern Brazil. Energy Build 2011;43:1712–22.
[7] Bates AJ, Sadler JP, Mackay R. Vegetation development over four years on two green roofs in the UK. Urban Forestry Urban Green 2013;12:98–108.
[8] Blank L, Vasl A, Levy S, Grant G, Kadas G, Dafni A, et al. Directions in green roof research: a bibliometric study. Build Environ 2013;66:23–8.
[9] Berardi U. Clarifying the new interpretations of the concept of sustainable building. Sustain Cities Soc 2013;8(1):72–8.
[10] Williams NSG, Rayner JP, Raynor KJ. Green roofs for a wide brown land: opportunities and barriers for rooftop greening in Australia. Urban Forest Urban Green 2010;9:245–51.
[11] Peri G, Traverso M, Finkbeiner M, Rizzo G. The cost of green roofs disposal in a life cycle perspective: covering the gap. Energy 2012;48:406–14.
[12] Shimmy. A brief history of roof gardens; 2012. <http://www.heathershimmin.com/a-brief-history-of-roof-gardens>.
[13] Kohler M, Schmidt M, Grimme FW, Laar M, de Assuncao PVL, Tavares S. Green roofs in temperate climates and in the hot-humid tropics-far beyond the aesthetics. Environ Manage Health 2002;13(4):382–91.
[14] Eisenman T. Raising the bar on green roof design. Landscape Archit 2006;96(11):22–9.
[15] Dunnett N, Kingsbury N. Planting green roofs and living walls. 2nd ed. Portland (OR): Timber Press; 2008.
[16] Liu KY, Baskaran BA. NRCC-46412: thermal performance of green roofs through field evaluation. Ottawa, Ontario: National Research Council Canada; 2003 [p. 1–10].
[17] 2012 Award Winners. The 2012 green roof and wall awards of excellence, green roofs for healthy cities. <http://www.greenroofs.org/index.php/events/awards-of-excellence/2012-award-winners>.
[18] Lanham JK. Thermal performance of green roofs in cold climates. Master Thesis. Queen's University; 2007.
[19] Sailor DJ. A green roof model for building energy simulation programs. Energy Build 2008;40:1466–78.
[20] Alexandri A, Jones P. Developing a one-dimensional heat and mass transfer algorithm for describing the effect of green roofs on the built environment: comparison with experimental results. Build Environ 2007;42:2835–49.
[21] Kumar R, Kaushik SC. Performance evaluation of green roof and shading for thermal protection of buildings. Build Environ 2005;40(11):1505–11.
[22] Pérez G, Rincón L, Vila A, González J, Cabeza LF. Green vertical systems for buildings as passive systems for energy savings. Appl Energy 2011;88(12):4854–9.
[23] Castleton HF, Stovin V, Beck SBM, Davison JB. Green roofs; building energy savings and the potential for retrofit. Energy Build 2010;42:1582–91.
[24] Morau D, Rakotondramiarana H, Andriamamonjy AI. Simple model for the theoretical survey of the green roof thermal behavior. J Technol Innovat Renew Energy 2012;1(2):92–102.
[25] Jaffal I, Ouldboukhitine S, Belarbi R. A comprehensive study of the impact of green roofs on building energy performance. Renew Energy 2012;43:157–64.
[26] Chen CF. Performance evaluation and development strategies for green roofs in Taiwan: a review. Ecol Eng 2013;52:51–8.
[27] Saiz S, Kennedy C, Bass B, Pressnail K. Comparative life cycle assessment of standard and green roofs. Environ Sci Technol 2006;40:4312–6.
[28] Kim J, Hong T, Koo CW. Economic and environmental evaluation model for selecting the optimum design of green roof systems in elementary schools. Environ Sci Technol 2012;46(15):8475–83.
[29] Oberndorfer E, Lundholm J, Bass B, Coffman RR, Doshi H, Dunnett N, et al. Green roofs as urban ecosystems: ecological structures, functions, and services. Bioscience 2007;57(10):823–33.
[30] Nagase A, Dunnett N. Establishment of an annual meadow on extensive green roofs in the UK. Landscape Urban Plan 2013;112:50–62.
[31] Theodosiou T. Green roofs in buildings: thermal and environmental behaviour. Adv Build Energy Res 2009;3:271–88.
[32] Yang J, Yu Q, Gong P. Quantifying air pollution removal by green roofs in Chicago. Atmos Environ 2008;42(31):7266–73.
[33] Berndtsson JC. Green roof performance towards management of runoff water quantity and quality: a review. Ecol Eng 2010;36:351–60.
[34] Liu KY, Baskaran A. Using garden roof systems to achieve sustainable building envelopes, vol. 65. Construction Technology Update, National Research Council Canada; 2005 [p. 1–6].
[35] Sun T, Bou-Zeid E, Wang ZH, Zerba E, Ni GH. Hydrometeorological determinants of green roof performance via a vertically-resolved model for heat and water transport. Build Environ 2013;60:211–24.
[36] Molineux CJ, Fentiman CH, Gange AC. Characterising alternative recycled waste materials for use as green roof growing media in the UK. Ecol Eng 2009;35(10):1507–13.
[37] Jim CY, Tsang SW. Ecological energetics of tropical intensive green roof. Energy Build 2011;43:2696–704.
[38] MacIvor JS, Margolis L, Puncher CL, Matthews BJC. Decoupling factors affecting plant diversity and cover on extensive green roofs. J Environ Manage 2013;130:297–305.
[39] Dinsdale S, Pearen B, Wilson C. Feasibility study for green roof application on queen's university campus. Queen's Physical Plant Services; 2006.
[40] Wong NH, Cheong DKW, Yan H, Soh J, Ong CL, Sia A. The effects of rooftop garden on energy consumption of a commercial building in Singapore. Energy Build 2003;35:353–64.
[41] Emilsson T. Vegetation development on extensive vegetated green roofs: influence of substrate composition, establishment method and species mix. Ecol Eng 2008;33(3–4):265–77.
[42] Rowe DB, Getter KL, Durhman AK. Effect of green roof media depth on Crassulacean plant succession over seven years. Landscape Urban Plan 2012;104(3–4):310–9.
[43] Wolf D, Lundholm JT. Water uptake in green roof microcosms: effects of plant species and water availability. Ecol Eng 2008;33:179–86.
[44] Nagase A, Dunnett N. Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity. Landscape Urban Plan 2010;97:318–27.
[45] Lundholm J, MacIvor JS, MacDougall Z, Ranalli M. Plant species and functional group combinations affect green roof ecosystem functions. PLoS ONE 2010;3:9677.
[46] Palla A, Gnecco I, Lanza LG. Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof. J Hydrol 2009;379(1–2):193–204.
[47] She N, Pang J. Physically based green roof model. J Hydrol Eng 2010;15(6):458–64.
[48] Bianchini F, Hewage K. Probabilistic social cost-benefit analysis for green roofs: a lifecycle approach. Build Environ 2012;58:152–62.
[49] Ascione F, Bianco N, Rossi FD, Turni G, Vanoli GP. Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning? Appl Energy 2013;104:845–59.
[50] Kohler M, Poll PH. Long-term performance of selected old Berlin green roofs in comparison to younger extensive green roofs in Berlin. Ecol Eng 2010;36:722–9.
[51] MacIvor JS, Ranalli MA, Lundholm JT. Performance of dryland and wetland plant species on extensive green roofs. Ann Bot 2011;107(4):671–9.
[52] Sutton RK, Harrington JA, Skabelund L, MacDonagh P, Coffman PR, Koch G. Prairie-based green roofs: literature, templates, and analogs. J Green Build 2012;7(1):143–72.
[53] Schweitzer O, Erell E. Evaluation of the energy performance and irrigation requirements of extensive green roofs in a water-scarce Mediterranean climate. Energy and Buildings 2014;68:25–32.
[54] Durhman AK, Rowe DB. Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa. HortScience 2007;42(3):588–95.
[55] Getter KL, Rowe DB. The role of extensive green roofs in sustainable development. HortScience 2006;41(5):1276–85.
[56] Blanusa T, Vaz Monteiro MM, Fantozzi F, Vysini E, Li Y, Cameron RWF. Alternatives to Sedum on green roofs: Can broad leaf perennial plants offer better 'cooling service'? Build Environ 2013;59:99–106.
[57] Getter KL, Rowe DB. Selecting plants for extensive green roofs in the United States. Extension Bulletin E-3047, Michigan State University; July 2008.
[58] Rosenzweig C, Solecki WD, Parshall L, Chopping M, Pope G, Goldberg R. Characterizing the urban heat island in current and future climates in New Jersey. Environ Hazards 2005;6(1):51–62.
[59] Xie HJ, Chang NB, Daranpob A, Prado D. Assessing the long-term urban heat island in san antonio, Texas based on MODIS/Aqua Data. In: 20th biennial workshop on aerial photography, videography, and high resolution digital imagery for resource assessment, 4–6 October, 2005. Weslaco, Texas; 2005.
[60] Weng Q, Lu D, Schubring J. Estimation of land surface temperature-vegetation abundance relationship for urban heat island studies. Remote Sens Environ 2004;89(4):467–83.
[61] Liu K, Minor J. Performance evaluation of an extensive green roof. In: Third annual greening rooftops for sustainable communities conference, Awards and Trade Show. Washington, DC; 4–6 May 2005.
[62] Takebayashi H, Moriyama M. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. Build Environ 2007;42(8):2971–9.
[63] Santamouris M. Cooling the cities – a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy 2012; in press.
[64] Sathien K, Techato K, Taweekun J. Using vertical green as material for complying building energy code. Adv Mater Res 2013;622:1035–8.
[65] Fang CF. Evaluating the thermal reduction effect of plant layers on rooftops. Energy Build 2008;40(6):1048–52.

[66] Qin X, Wu X, Chiew YM, Li Y. A green roof test bed for stormwater management and reduction of urban heat island effect in Singapore. Brit J Environ Clim Change 2012;2(4):410–20.
[67] Chan ALS, Chow TT. Evaluation of overall thermal transfer value (OTTV) for commercial buildings constructed with green roof. Appl Energy 2013;107:10–24.
[68] Tabares-Velasco PC, Zhao M, Peterson N, Srebric J, Berghage R. Validation of predictive heat and mass transfer green roof model with extensive green roof field data. Ecol Eng Ecol Eng 2012;47:165–73.
[69] Green Roof Energy Calculator, v.2, Green Building Research Laboratory; 2013. <http://greenbuilding.pdx.edu/GR_CALC_v2/grcalc_v2.php#retain>.
[70] Niu H, Clark C, Zhou J, Adriaens P. Scaling of economic benefits from green roof implementation in Washington, DC. Environ Sci Technol 2010;44(11):4302–8.
[71] Ouldboukhitine SE, Belarbi R, Jaffal I, Trabelsi A. Assessment of green roof thermal behavior: a coupled heat and mass transfer model. Build Environ 2011;46:2624–31.
[72] Simmons MT, Gardiner B, Windhager S, Tinsley J. Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. Urban Ecosyst 2008;11(4):339–48.
[73] Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G. Analysis of the green roof thermal properties and investigation of its energy performance. Energy Build 2001;33(7):719–29.
[74] Jim CY. Effect of vegetation biomass structure on thermal performance of tropical green roof. Landscape Ecol Eng 2012;8:173–87.
[75] Olivieri F, Di Perna C, D'Orazio M, Olivieri L, Neila J. Experimental measurements and numerical model for the summer performance assessment of extensive green roofs in a mediterranean coastal climate. Energy Build 2013;63:1–14.
[76] Getter KL, Rowe DB, Andresen JA, Wichman IS. Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate. Energy Build 2011;43:3548–57.
[77] Zhao M, Srebric J. Assessment of green roof performance for sustainable buildings under winter weather conditions. J Central South Univ 2012;19(3):639–44.
[78] Pandey S, Hindoliya DA, Mod R. Experimental investigation on green roofs over buildings. Int J Low-Carbon Technol 2013;8:37–42.
[79] Spala A, Bagiorgas HS, Assimakopoulos MN, Kalavrouziotisa J, Matthopoulos D, Mihalakakou G. On the green roof system. Selection, state of the art and energy potential investigation of a system installed in an office building in Athens, Greece. Renewable Energy 2008;33:173–7.
[80] Nardini A, Andri S, Crasso M. Influence of substrate depth and vegetation type on temperature and water runoff mitigation by extensive green roofs: shrubs versus herbaceous plants. Urban Ecosyst 2012;15:697–708.
[81] Carpenter J, Zhou J. Life cycle analysis of a St. Louis flat roof residential retrofit for improved energy efficiency. In: Proc. ICSDEC 2012-building energy use modelling and, energy efficiency; 2013. p. 20–8.
[82] Sailor DJ, Elley TB, Gibson M. Exploring the building energy impacts of green roof design decisions – a modeling study of buildings in four distinct climates. J Build Phys 2011;35(4):372–91.
[83] Saadatian O, Sopian K, Salleh E, Lim CH, Riffat S, Saadatian E, et al. A review of energy aspects of green roofs. Renew Sustain Energy Rev 2013;23:155–68.
[84] Alexandri E, Jones P. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Build Environ 2008;43(4):480–93.
[85] Gill SE, Handley JF, Ennos AR, Pauleit S. Adapting cities for climate change: the role of green infrastructure. Built Environ 2007;33:115–33.
[86] Kosareo L, Ries R. Comparative environmental life cycle assessment of green roofs. Build Environ 2007;42:2606–13.
[87] Ihara T, Kikegawa Y, Asahi K, Genchi Y, Kondo H. Changes in year-round air temperature and annual energy consumption in office building areas by urban heat-island countermeasures and energy-saving measures. Appl Energy 2008;85(1):12–25.
[88] Li JF, Wai OWH, Li YS, Zhan JM, Ho YA, Li J, et al. Effect of green roof on ambient CO2 concentration. Build Environ 2010;45:2644–51.
[89] Speak AF, Rothwell JJ, Lindley SJ, Smith CL. Reduction of the urban cooling effects of an intensive green roof due to vegetation damage. Urban Clim 2013;3:40–55.
[90] Susca T, Gaffin SR, Dell'Osso GR. Positive effects of vegetation: urban heat island and green roofs. Environ Pollut 2011;159:2119–26.
[91] Wong JKW, Lau LSK. From the 'urban heat island' to the 'green island'? A preliminary investigation into the potential of retrofitting green roofs in Mongkok district of Hong Kong. Habitat Int 2013;39:25–35.
[92] Smith K, Roeber P. Green roof mitigation potential for a proxy future climate scenario in Chicago, Illinois. J Appl Meteorol Climatol 2011;50:507–22.
[93] Savio P, Rosenzweig C, Solecki WD, Slosberg RB. Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces. New York City regional heat island initiative. The New York State Energy Research and Development Authority; 2006.
[94] Chen H, Ooka R, Huang H, Tsuchiya T. Study on mitigation measures for outdoor thermal environment on present urban blocks in Tokyo using coupled simulation. Build Environ 2009;44:2290–9.
[95] Ng E, Chen L, Wang Y, Chao Y. A study on the cooling effects of greening in a high-density city: an experience from Hong Kong. Build Environ 2012;47:256–71.
[96] Lazzarin RM, Castellotti F, Busato F. Experimental measurements and numerical modeling of a green roof. Energy Build 2005;37:1260–7.
[97] Feng C, Meng Q, Zhang Y. Theoretical and experimental analysis of the energy balance of extensive green roofs. Energy Build 2010;42:959–65.
[98] Rezaei F. Evapotranspiration rates from extensive green roof plant species, M.S. Thesis. Agricultural and Biological Engineering. State College, PA: The Pennsylvania State University; 2005.
[99] Berghage R, Jarrett A, Beattie D, Kelley K, Husain S, Rezai F, Long B, Negassi A, Cameron R, Hunt W. Quantifying evaporation and transpiration water losses from green roofs and green roof media capacity for neutralizing acid rain. National Decentralized Water Resources Capacity Development Project; 2007.
[100] Currie BA, Bass B. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. Urban Ecosyst 2008;11:409–22.
[101] Zhang X, Shen L, Tam VWY, Lee WWY. Barriers to implement extensive green roof systems: a Hong Kong study. Renew Sustain Energy Rev 2012;16(1):314–9.
[102] Getter KL, Rowe DB, Robertson GP, Cregg BM, Andresen JA. Carbon sequestration potential of extensive green roofs. Environ Sci Technol 2009;43(19):7564–70.
[103] Rowe DB. Green roofs as a means of pollution abatement. Environ Pollut 2011;159:2100–10.
[104] Currie BA, Bass B. Estimate of air pollution mitigation with green plants and green roofs using the UFORE model. In: Proceedings of third annual greening rooftops for sustainable communities conference. Washington, DC; 4–6 May 2005.
[105] Deutsch B, Whitlow H, Sullivan M, Savineau A. Re-greening Washington, DC. A Green Roof Vision Based on Quantifying Storm Water and Air Quality Benefits; 2005.
[106] Speak AF, Rothwell JJ, Lindley SJ, Smith CL. Metal and nutrient dynamics on an aged intensive green roof. Environ Pollut 2014;184:33–43.
[107] Tan PY, Sia A. A pilot green roof research project in Singapore. In: Proceedings of third annual greening rooftops for sustainable communities conference, Awards and Trade Show, Washington, DC; May 4–6, 2005.
[108] Stathopoulou E, Mihalakakou G, Santamouris M, Bagiorgas HS. Impact of temperature on tropospheric ozone concentration levels in urban environments. J Earth Syst Sci 2008;117(3):227–36.
[109] Sarrat C, Lemonsu A, Masson V, Guedalia D. Impact of urban heat island on regional atmospheric pollution. Atmos Environ 2006;40:1743–58.
[110] Hathaway AM, Hunt WF, Jennings GD. A field study of green roof hydrologic and water quality performance. Am Soc Agric Biol Eng 2008;51(1):37–44.
[111] Getter KL, Rowe DB, Andersen JA. Quantifying the effect of slope on extensive green roof stormwater retention. Ecol Eng 2007;31:225–31.
[112] Villarreal EL, Bengtsson L. Response of a Sedum green-roof to individual rain events. J Ecol Eng 2005;25:1–7.
[113] Moran A, Hunt B, Jennings G. A North Carolina field study to evaluate green roof runoff quantity, runoff quality, and plant growth. In: Proceedings of the 2nd North American green roof conference: greening rooftops for sustainable communities 2004, Portland, OR, June 2–4. Toronto: The Cardinal Group; p. 446–60.
[114] Dunnett N, Nagase A, Booth R, Grime P. Influence of vegetation composition on runoff in two simulated green roof experiments. Urban Ecosyst 2008;11:385–98.
[115] Bengtsson L. Peak flows from thin Sedum-moss roof. Nord Hydrol 2005;36(3):269–80.
[116] DeNardo JC, Jarrett AR, Manbeck HB, Beattie DJ, Berghage RD. Stormwater mitigation and surface temperature reduction by green roofs. Trans ASABE 2005;48(4):1491–6.
[117] VanWoert ND, Rowe DB, Andresen JA, Rugh CL, Fernandez RT, Xiao L. Green roof stormwater retention: Effects of roof surface, slope, and media depth. J Environ Qual 2005;34:1036–44.
[118] DeNardo JC, Jarrett AR, Manbeck HB, Beattie DJ, Berghage RD. Stormwater detention and retention abilities of green roofs. In: World water and environmental resources congress, June 23–26, 2003. PA, United States: ASCE, Philadelphia; 2003. p. 1639–45.
[119] Fioretti R, Palla A, Lanza LG, Principi P. Green roof energy and water related performance in the Mediterranean climate. Build Environ 2010;45:1890–904.
[120] Kikuchi S, Koshimizu H. A comparison of green roof systems with conventional roof for the storm water runoff. Spat Plan Sustain Dev Strategies Sustain 2013:287–303.
[121] Mickovski SB, Buss K, McKenzie BM, Sokmener B. Laboratory study on the potential use of recycled inert construction waste material in the substrate mix for extensive green roofs. Ecol Eng 2013, in press.
[122] Roehr D, Kong Y. Runoff reduction effects of green roofs in Vancouver, BC, Kelowna, BC, and Shanghai, PR China. Can Water Res J 2010;35(1):53–68.
[123] Stovin V, Vesuviano G, Kasmin H. The hydrological performance of a green roof test bed under UK climatic conditions. J Hydrol 2012;414–415:148–61.
[124] Vijayaraghavan KU, Joshi M, Balasubramanian R. A field study to evaluate runoff quality from green roofs. Water Res 2012;46:1337–45.
[125] Berndtsson JC, Bengtsson L, Jinno K. Runoff water quality from intensive and extensive vegetated roofs. Ecol Eng 2009;35(3):369–80.
[126] Stovin V, Dunnett N, Hallam A. Green Roofs – getting sustainable drainage off the ground. In: 6th International conference of sustainable techniques and strategies in urban water management (Novatech 2007). Lyon, France; 2007. p. 11–8.

[127] Mentens J, Raes D, Hermy M. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape Urban Plan 2006;77:217–26.
[128] Van Renterghem T, Botteldooren D. In situ measurements of sound propagating over extensive green roofs. Build Environ 2011;46:729–38.
[129] Van Renterghem T, Botteldooren D. Reducing the acoustical facade from road traffic with green roofs. Build Environ 2009;44:1081–7.
[130] Van Renterghem T, Hornikx M, Forssen J, Botteldooren D. The potential of building envelope greening to achieve quietness. Build Environ 2013;61:34–44.
[131] Connelly M, Hodgson M. Sound transmission loss of green roofs. In: Sixth annual greening rooftops for sustainable communities conference. Awards and Trade Show; 2008.
[132] Connelly M, Hodgson M. Sound transmission loss of extensive green roofs-field test results. Can Acoust 2008;36(3):74–5.
[133] Yang HS, Kang J, Choi MS. Acoustic effects of green roof systems on a low-profiled structure at street level. Build Environ 2012;50:44–55.
[134] Connelly M, Hodgson M. Laboratory experimental investigation of the acoustical characteristics of vegetated roofs. J Acoust Soc Am 2011;129:2393.
[135] Peng LLH, Jim CY. Green-roof effects on neighborhood microclimate and human thermal sensation. Energies 2013;6(2):598–618.
[136] Bianchini F, Hewage K. How "green" are the green roofs? Lifecycle analysis of green roof materials. Build Environ 2012;48:57–65.
[137] Donovan R, Sadler J, Bryson J. Urban biodiversity and sustainable development. Eng Sustain 2005:105–14.
[138] Baumann N. Ground-nesting birds on green roofs in Switzerland: preliminary observations. Urban Habitats 2006;4:37–50.
[139] Francis RA, Lorimer J. Urban reconciliation ecology: the potential of living roofs and walls. J Environ Manage 2011;92(6):1429–37.
[140] MacIvor JS, Lundholm J. Insect species composition and diversity on intensive green roofs and adjacent level-ground habitats. Urban Ecosyst 2011;14:225–41.
[141] Sadler J, Bates A, Donovan R, Bodnar S. Building for biodiversity: accommodating people and wildlife in cities. In: Niemela J, Breusye JH, Guntenspergen G, McIntyre NE, Elmqvist T, James P, editors. Urban Ecology. Patterns, Processes and Applications. Oxford University Press, Oxford; 2011. p. 286–97.
[142] Koehler M. Plant survival research and biodiversity: lessons from Europe. In: Greening rooftops for sustainable communities. Chicago; 2003. p. 313–22.
[143] Brenneisen S. Space for urban wildlife: designing green roofs as habitats in Switzerland. Urban Habitat 2006;4:27–36.
[144] Ksiazek K, Fant J, Skogen K. An assessment of pollen limitation on Chicago green roofs. Landscape Urban Plan 2012;107:401–8.
[145] Baik J, Kwak K, Park S, Ryu Y. Effects of building roof greening on air quality in street canyons. Atmos Environ 2012;61:48–55.
[146] Whittinghill LJ, Rowe DB, Cregg BM. Evaluation of vegetable production on extensive green roofs. Agroecol Sustain Food Syst 2013;37(4):465–84.
[147] Pérez G, Vila A, Rincón L, Solé C, Cabeza LF. Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material. Appl Energy 2012;97:347–54.
[148] Hiu H, Clark C, Zhouo J, Adriaens P. Scaling of economic benefits from green roof implementation in Washington DC. Environ Sci Technol 2010;44:4302–8.
[149] Tsang SW, Jim CY. Game-theory approach for resident coalitions to allocate green-roof benefits. Environ Plan 2011;43:363–77.
[150] Hui SCM. Benefits and potential applications of green roof systems in Hong Kong. In: Proceedings of the 2nd megacities international conference; 2006. p. 351–60.
[151] Carter T, Keeler A. Life-cycle cost-benefit analysis of extensive vegetated roof systems. J Environ Manage 2008;87(3):350–63.
[152] Popescu D, Bienert S, Schützenhofer C, Boazu R. Impact of energy efficiency measures on the economic value of buildings. Appl Energy 2012;89:454–63.
[153] Braaker S, Ghazoul J, Obrist MK, Moretti M. Habitat connectivity shapes urban arthropod communities-the key role of green roofs. Ecology; 2013, in press.
[154] Proietti S, Desideri U, Sdringola P, Zepparelli F. Carbon footprint of a reflective foil and comparison with other solutions for thermal insulation in building envelope. Appl Energy 2013;112:843–55.
[155] Zheng G, Jing Y, Huang H, Gao Y. Application of improved grey relational projection method to evaluate sustainable building envelope performance. Appl Energy 2010;87:710–20.
[156] Brenneisen S. Green roofs: How nature returns to the city. Acta Horticulturae 2004;643:289–93.
[157] Carter T, Fowler L. Establishing green roof infrastructure through environmental policy instruments. Environ Manage 2008;42(1):151–64.
[158] Berardi U. Stakeholders' influence on the adoption of energy saving technologies in Italian homes. Energy Policy 2013;60:520–30.
[159] GhaffarianHoseini AH, GhaffarianHoseini A, Makaremi N, GhaffarianHoseini M. The Concept of Zero Energy Intelligent Buildings (ZEIB): A Review of Sustainable Development for Future Cities. British Journal of Environment and Climate Change 2012;2(4):339–67.